AR-005-742

THE MEASUREMENT OF SURFACE REFLECTIVITY AT MILLIMETRE WAVELENGTHS

R. W. DIXON AND K. J. GAYLOR

MATERIALS RESEARCH LABORATORY

DSTO

The Measurement of Surface Reflectivity at Millimetre Wavelengths

P.W. Dixon and K.J. Gaylor

MRL Technical Note
MRL-TN-559

Abstract

An experimental facility has been constructed to measure the surface reflectivity of materials at millimetre wavelengths. The facility can be used to measure the bistatic, monostatic or specular reflection from flat samples at horizontal, vertical or cross polarisations. The reflectivity of some representative materials of defence interest has been measured at 35 GHz.

Published by DSTO Materials Research Laboratory
Cordite Avenue, Maribyrnong, Victoria, 3032 Australia
Telephone: (03) 319 3887
Fax: (03) 318 4536

AR No. 005-729

Contents

The Measurement of Surface Reflectivity at Millimetre Wavelengths

1. Introduction

An active millimetre wave (MMW) experimental facility for measuring surface reflectivity of defence-related materials has been designed and constructed. The work was part of a DSTO task on Passive Millimetre-Wave Countersurveillance. The objective of the task was to undertake research on techniques for reducing susceptibility of military targets to detection by surveillance systems operating in the MMW region. This facility contributed to the task by providing a means for measuring the reflectivity of target materials and modified target surfaces.

Millimetre wave radiation exhibits relatively low-loss atmospheric propagation at 35 GHz and 94 GHz and gives useful transmission through fogs and obscurants. The advantages of MMW radiation compared with microwave radiation include broader bandwidths, higher spatial resolution, greater directionality and the ability to use smaller equipment. These recognised advantages, and the increasing sophistication of advanced MMW technology have lead to the increased use of MMW systems and sub-systems on the battlefield. A requirement to investigate the reflection properties of materials at MMW frequencies and possible countersurveillance techniques has therefore developed [1].

Applications of millimetre waves on the battlefield include air-borne surveillance, precision guided munitions, gun fire-control-radar and tactical point-to-point communication. Both airborne surveillance and precision guided munitions use MMW radiometers to measure the thermal radiation emitted or reflected by targets and their background. Metal targets evidence a high reflectivity when compared with the reflectivity of the background terrain. Because they reflect the sky radiation, metal targets are recorded by the radiometer as low temperature thermal sources while the background is recorded as an apparent high temperature (280-300 K). The temperature difference between the target and the background will depend on the reflectivity of the target materials, the sky temperature (which changes with weather and observation frequency) and the MMW properties of the environment.

This technical note describes an active MMW experimental facility for measuring the surface reflectivity of materials. The materials were chosen as representative of those that might be associated with defence-related targets. The facility is capable of measuring the bistatic, monostatic or specular reflection with horizontal or vertical polarisation in a two dimensional plane. Results can also be obtained to measure the reflected horizontal polarisation when vertical polarisation is incident on the target and vice versa, (i.e. cross polarisation measurements).

2. MMW Scattering and Reflectivity

The scattering or signal return of a target when illuminated by millimetre waves is a function of the incident radiation, i.e. polarisation and wavelength, the target properties which include target size, shape, surface roughness and reflectivity, and the system geometry, i.e. the incident and detection angles. The signal returned directly back to the source (called backscatter) can be calculated for many simple shapes (with smooth surfaces) as described in many texts on radar cross section such as Knott et al [2] and Crispin and Siegel [3]. More complicated targets can be modelled as being composed of a number of simple shapes such as spheres, cylinders and flat plates, the final result being a superposition of each individual contribution. For example, the backscattered cross-section of a flat plate, calculated by assuming physical optics conditions, is given by

$$\sigma(\phi) = 64\pi\,(a^2 b^2/\lambda^2)\cos^2\phi\,[\sin(2ka\sin\phi)/2ka\sin\phi]^2 \tag{1}$$

where $k = 2\pi/\lambda$ is the wave number, ϕ is the incident angle and the plate has the dimension of 2a for width and 2b for height. This formula is accurate for either vertical or horizontal polarisation and for incident angles less than 45 degrees. For greater angles it is necessary to use Geometrical Diffraction Theory (GDT) as described by Ross [4]. Using GDT, polarisation and edge effects become more apparent.

3. Measurement of Reflectivity

There are three common ways to examine the reflectivity of a flat surface. These are:

1. Bistatic reflectivity measurements, where the source and detector are spatially separated. This function depends on the angle between source and detector, and the relative angle of the reflecting surface. The bistatic reflectivity for a flat metal plate is shown in figure 1, for incident angles between 0 and 90 degrees, and bistatic angles between 0 and 180 degrees.

2. Backscatter measurements, a subset of case 1, where the source and the detector are co-incident (or nearly co-incident). The reflecting surface may be rotated to obtain the backscattered reflectance as a function of incident angle.

3. Specular reflection, also a subset of case 1, where the source and detector angles bisect the normal of the scattering surface.

Reflection measurements are made by comparing the signal return from a metal sample (considered as a standard) with that from the sample under test. For this to be accurate the samples must be the same size and shape.

The flat plate is used as the sample as it is easy to produce and has a known reflection pattern. The linear dimensions of the plate are governed by the need for a plane wave to be incident on the target and to minimise edge effects. The former is obtained by applying the far field criterion as discussed by Kougaumjian and Peters [5] which requires that

$$R \geq 2L^2/\lambda \tag{2}$$

where L is the largest dimension of the target, λ is the wavelength and R is the distance between target and source horn. The plate should be greater than 5 wavelengths in size to minimise edge effects but no greater than 15 wavelengths to maximise angular resolution (reference [2], p. 301). The horn and target should be greater than L^2/d above the support bench to minimise bench reflections where d is the size of the largest aperture of the horn.

4. Experimental Facility

A schematic of the experimental facility is shown in figure 2. The facility consists of a source horn directing radiation at a target attached to a rotating table. Scattered energy reflected by the target is collected by both the source horn and a movable bistatic detector horn to obtain the backscattered reflection and bistatic reflection respectively. The source, rotating table and bistatic detector positions are computer controlled.

Data acquisition is also controlled by the computer. A computer program called MMWAVES, written in TURBO PASCAL - Version 3 allows the operator to select the desired reflectivity measurement or analysis function. The program controls all instruments via the computer's interface boards. The sides and top of the supporting bench for the facility are lined with radar absorbing material as shown in figures 3 and 4. Full details of the equipment used can be found in table 1. Relevant distances and sizes are detailed in table 2.

4.1 Incident and Backscatter Detectors

The incident and backscatter detectors are shown in figure 4 and detailed in schematic form in figure 5. The source output is directed along a Ka band waveguide to a pyramidal horn that is directed at the target. The incident power is monitored by a crystal detector attached to a directional coupler with 20 dB coupling. Scattered energy that is reflected back into the horn is detected by another crystal detector via a directional coupler with 6 dB coupling. The source is protected from backscatter interference by a 25 dB ferrite isolator. The output power is switched by the modulator which is controlled by a digital I/0 board in the computer. The output polarisation can be changed by inserting a short length of 90° rotation waveguide. The stub tuner is used to correct directivity errors of the directional coupler and cancel unwanted signals from the surroundings. This is done by removing the target holder and adjusting the stub tuner until no signal is received at the backscatter detector.

4.2 Target Holder

The target holder as shown in figures 6 and 7 is designed to mount the flat plate samples accurately and also to have a low reflectivity. The low reflectivity is obtained by using perspex which has a low reflectivity at MMW wavelengths, and by shaping the surfaces of the holder so that no large flat surfaces are present. The back of the sample holder is also covered with radar absorbing material to further decrease spurious reflections. Samples plates are held by a vacuum system and are positioned in the centre of the holder head. The target holder is attached to a precision rotating table, which is computer controlled (figure 7). The samples are arranged so that their front surface is level with the axis of rotation of the rotating table.

4.3 Bistatic Detector

The bistatic detector is mounted on a movable base (figure 8) that can be rotated through an arc of 90 degrees. The detector consists of a pyramidal horn attached to a crystal detector mounted on a perspex cylindrical stand. The detector can move in either direction at a constant speed of approximately 2 degrees per second. A 10-turn potentiometer on one of the wheels of the mobile base provides a DC signal proportional to the bistatic angle of the detector.

4.4 Alignment

A small HeNe laser was used to set the horns and target on the same horizontal plane. The laser was set-up to be co-axial with the centre of the waveguide and source horn. This was used to set the waveguide at the same level as the centre of the target and, by using a polished sample, the bistatic detector could also be set level. Accurate positioning and repositioning of samples was obtained by the use of jigs and spacers.

5. Samples

The samples to be tested were flat, square plates of two sizes, 75 mm and 100 mm square. According to the far field criterion (equation 2) the minimum range required at 35 GHz is 2.34 metres for a 100 mm square plate, and 1.30 metres for a 75 mm square plate. The source horn - sample separation distance used was 1.2 m. Although these distances do not exactly agree with the far field criterion, they were considered acceptable because (a) comparisons between similar sample sizes were made and (b) the far field criterion is only used as a guide. Results shown later indicate that good agreement between experiment and theory is obtained, indicating that these assumptions are valid.

The samples were approximately 9 and 12 wavelengths in length for the 75 and 100 mm square plates respectively, thus satisfying the other size criterion mentioned earlier. Full details of the samples studied are listed in table 3. The reference plates had a measured flatness better than 0.05 mm. The conductive paint sample had a flatness of 0.5 mm but all other samples had a flatness of 0.10 mm or better. A paint thickness of 0.08 mm was used on the Army paint samples and a thickness of 0.02 mm for the conductive paint samples.

6. Data Acquisition and Processing

Acquisition of data was performed by an IWATSU Digital Memory Device using four channels of 4096 samples/channel. The bistatic and backscatter detectors were recorded by 12 bit ADCs while the incident detector and the bistatic angle position were recorded by 8 bit ADCs. Data were recorded every 2 ms as the target rotated. The rotation rate of the target was preset to give a resolution of 40 samples/degree of rotation. Data acquisition intervals of 10 ms were used when the bistatic detector was rotated around the stationary target.

Zero offset of the amplifiers for the detectors was allowed for by recording the detector output with the source power removed via the modulator for a short period (usually about 100 samples which is 0.2 s for 2 ms acquisition intervals or 1.0 s for 10 ms intervals) at the start and end of the data acquisition period. The average offset signal level was calculated for these power-off periods to obtain the amplifier offset for each detector. The appropriate offset was then subtracted from the recorded

detector signal. The timing sequence for data acquisition events (power ON/OFF etc.) is shown in figure 9.

The relative reflection of the target sample when compared to a reference plate is

$$\text{Relative Reflection} = \frac{S_D(\text{sample})}{S_D(\text{reference})} \times \frac{P_{ave}(\text{reference})}{P_{ave}(\text{sample})}$$

where P_{ave} is the average of the source signal level for the time of rotation and S_D is the detector signal for the sample or reference as appropriate. The second term of the above equation is required to correct for changes in source signal level between the reference run and sample run. After processing, the bistatic and backscatter detector data were stored on floppy disk for later analysis.

7. Measurement Options

To obtain the reflectivity of a sample, the sample signal is compared with the equivalent signal from a metal plate that is used as a reference. The reference is assumed to behave as a perfect reflector and to follow the scattering pattern calculated by Ross [4]. In figure 10, the calculated scattering pattern from equation 1 is compared with results from the experimental facility. Because of the finite aperture of the horns, the experimental result will be the sum over a small range of angles. This will tend to smear the resulting pattern. The minima and maxima positions are in good agreement.

The computer program allows the operator to select either rotation of the target or movement of the bistatic detector. When the target is rotated, the backscatter and bistatic reflectivities are obtained as shown in figure 11 for a metal plate. If the bistatic detector is moved, the bistatic reflectivity is obtained for a fixed incident angle as shown in figure 12. It is also possible to both move the bistatic detector and rotate the target to obtain the specular reflection of the target. This is done by rotating the target quickly to a desired incident angle and then moving the bistatic detector until the specular peak has been passed. The target is then rotated to the next desired incident angle until the bistatic detector again passes the peak. This process is repeated until the bistatic detector reaches its maximum travel. The resultant data acquired from the bistatic detector are shown in figure 13. The peaks are extracted to give specular reflection points at incident angles incremented every 5 degrees.

8. Results

The scattering properties and reflectivity of the samples listed in table 3 were measured. All samples had the same general scattering pattern as the reference plate but varied in the strength of the signal return, thus indicating that all samples were uniformly flat. The specular reflection for incident angles between 0 and 40 degrees was measured for each sample. It was found that the specular reflectivity as compared to the reference did not vary significantly over this incident angle range. Table 4 gives the measured reflectivity for the samples and the measurement error. The figures quoted are the average of all runs on all similar samples. The 100 mm and 75 mm sample results have also been combined to give one figure. The results from the metal matrix composites (MMC) showed little difference so they are quoted under one figure.

The painted samples and conducting materials behave essentially as metal plates. The conductive paint gives only a 2 dB drop in reflectance but this could have been due to the non-flatness of the samples. The samples of glass, perspex, cardboard and kevlar had low to very low reflectance. Measurement of these materials with a metal backing gave high reflectivity thus showing that these materials were not absorbing the energy but were transmitting the incident radiation.

he measurement of vegetation was confined to leaves placed flat on a metal or cardboard sampl a single layer so to cover the whole plate. The leaves were obtained from a eucalyptus in the grounds of MRL. The tree was identified as a Black Peppermint *(Eucalpytus amygdalina)* [6]. Again there was no sign of scattering by the sample or any variation in specular reflectance as a function of incident angle when compared to the reference plate.

The leaves' reflectance is dependent on their moisture content as shown in figure 14. For example, when the samples were first measured soon after being picked they had a moisture content of 50% and gave a reflectivity of approximately 30% for both the metal backed and cardboard backed samples, thus indicating absorption of the radiation.

As the leaves dried out they became transparent to the millimetre waves and gave values approaching those for their backing material. It should be noted that the leaves dropped to 30% moisture content in only a few hours but increased their reflectivity to 80% for the metal backed sample. This result indicates that the concealment from MMW sensors offered by cut foliage is only of short duration.

9. Conclusions

This report has described a facility for measuring the reflectivity of flat samples at 35 GHz with horizontal, vertical or crossed polarisation. The facility can be used over the MMW frequency band 26.5 to 40 GHz with the appropriate source. The facility can be used with any similar source and detector if the range size and sample size criteria are followed for that source frequency.

To demonstrate the application of the equipment, the reflectivity for vertical polarisation at 35 GHz for various materials has been obtained. The reflectivity from leaves was shown to be dependent on the moisture content of the leaves.

10. Acknowledgements

The authors wish to thank Mr R.D. Williamson and Mr P.W. Star for their technical work on the facility. Mr Williamson also helped by identifying the eucalyptus sample.

11. References

1. Wendlandt, B.C.H. *An appraisal of millimetre wave stealth technology* (Internal Report). Maribyrnong, Vic.: Materials Research Laboratory.

2. Knott, E.F., Shaeffer, J.F. and Tuley, M.T. (1985). *Radar cross section*, Artech House, Chapter 6.

3. Crispin, J.W. and Siegel, K.M. (1968). *Methods of radar cross section analysis*. Academic Press, Part II.

4. Ross, R.A. (1966). Radar cross section of rectangular flat plates as a function of aspect angle. *IEEE Transactions on Antennas and Propagation*, AP-14, No. 3.

5. Kouyoumjian, R.G. and Peters, L. (1965). Range requirements in radar cross section measurements. *Proceedings of IEEE*, **53**, 8.

6. Williamson, R.D. MRL (private communication).

Table 1 Equipment and Apparatus Specifications

SOURCE AND BACKSCATTER DETECTOR

Source	ALPHA CMF717,	Power	50 mW
		Frequency	35 GHz
Horn	NARDA V637	Gain @ 35 GHz	17 dB
Stub tuner	HILGER W850 Single Probe Tuner		
6 dB coupler	HILGER W846 Directional coupler		6 dB
20 dB coupler	HILGER W848 Directional coupler		20 dB
Backscatter detector	HP R422A Crystal detector		300 mV/m
Incident detector	HILGER W862 Crystal detector		700 mV/m
Modulator	HUGHES 45211H-2100, ON-OFF Ratio		20 dB
Isolator	HUGHES 45111H-2000, Isolation		25 dB
Load (2)	HILGER W855 Matched Load		
Polarisation adaptor	V: straight waveguide		
	H: 90 degree twist waveguide		

BISTATIC DETECTOR

Horn	NARDA V637,	Gain @ 35 GHz	17 dB
Detector	HP R422A Crystal detector		300 mV/m

INSTRUMENTATION

Amplifier & LPF (3)	TEKTRONIX AM502, Low pass cutoff	100 Hz
Data Recorder	IWATSU DM7100 Digital Memory,	5 channels
Rotating Table	DAEDAL #20802-S, 8" Table	
Computer	IBM-PC Compatible	
	- NATIONAL Instruments GPIB Board	
	- DT2817 Digital I/O Board	
	- DAEDAL MC5000 Controller	

OTHER

Anechoic Absorber	RANTEC EHP-4CV	- Thickness	125 mm
		- Reflectance loss	> 50 dB
Waveguide	- rectangular [154-IEC-R230]		
	- frequency range 26.5-40 GHz		
Frequency band	- KA (WW2 designation)		
	- Ql (UK & IEC designation)		
Waveguide Flanges	- square UG599 [154-IEC-UBR-320]		
	- UK Pattern [154-IEC-PCR-320]		

Table 2 Relevant Distances/Sizes

Source horn - Target		1.2 m
Bistatic horn - Target [arc]		1.2 m
Height target centre - Bench top		230 mm
Height horn centre - Bench top		230 mm
Height anechoic absorber - Bench top		50 mm
Target size	- min. (holder size limit)	50 mm
	- max. (far field criterion)	100 mm

Table 3 List of Samples Tested

	Thickness (mm)	Sample Numbers (100/75 mm)
REFERENCE PLATES		
1. Steel sheet	1.2	1/1
ARMY CAMOUFLAGE PAINTS ON STEEL		
2. Green [Aust. Mil. 7650-ADE(M)146-1/3]	1.3	2/2
3. Brown [US Standard 595a-30219]	1.3	2/1
4. Black [US Standard 595a-37038]	1.3	2/1
CONDUCTING MATERIALS		
5. Titanium	1.7	-/1
	6.6	-/1
6. Metal matrix composites (MMC)		
- Silicon Carbide granules in Aluminium	7.0	-/2
- Silicon Carbide fibres in Titanium	4.6	-/1
7. Graphite-fibre epoxy composite (GFRP)	1.3	-/1
8. Conductive paint on PVC sheet	2.1	1/1
OTHER MATERIALS		
9. Perspex sheet	1.5	2/4
10. Glass sheet	2.0	-/1
11. Kevlar laminate	2.5	1/1
12. White posterboard	0.95	3/4
VEGETATION [Leaves taken from a Black Peppermint - Eucalyptus Amygdalina]		
13. LEAVES layered on metal plate (1)	-	-/1
14. LEAVES layered on posterboard (12)	-	-/1

Table 4 Reflection Results @ 35 GHz and Vertical Polarisation

	[%,± error]
REFERENCE PLATES	
1. Steel sheet	100, 0
ARMY CAMOUFLAGE PAINTS ON STEEL	
2. Green [Aust. Mil. 7650-ADE(M)146-1/3]	99, 3
3. Brown [US Standard 595a-30219]	99, 2
4. Black [US Standard 595a-37038]	99, 2
CONDUCTING MATERIALS	
5. Titanium	96, 9
6. Metal matrix composites (MMC)	97, 3
7. Graphite-fibre epoxy composite (GFRP)	96, 3
8. Conductive paint on PVC sheet	64, 7
OTHER MATERIALS	
9. Perspex sheet	14, 2
10. Glass sheet	25, 2
11. Kevlar laminate	3, 2
12. White posterboard	8, 1
VEGETATION [Leaves taken from a Black Peppermint - *Eucalyptus Amygdalina*]	
13. LEAVES layered on metal plate (1)	) - see graph
14. LEAVES layered on posterboard (12)	)

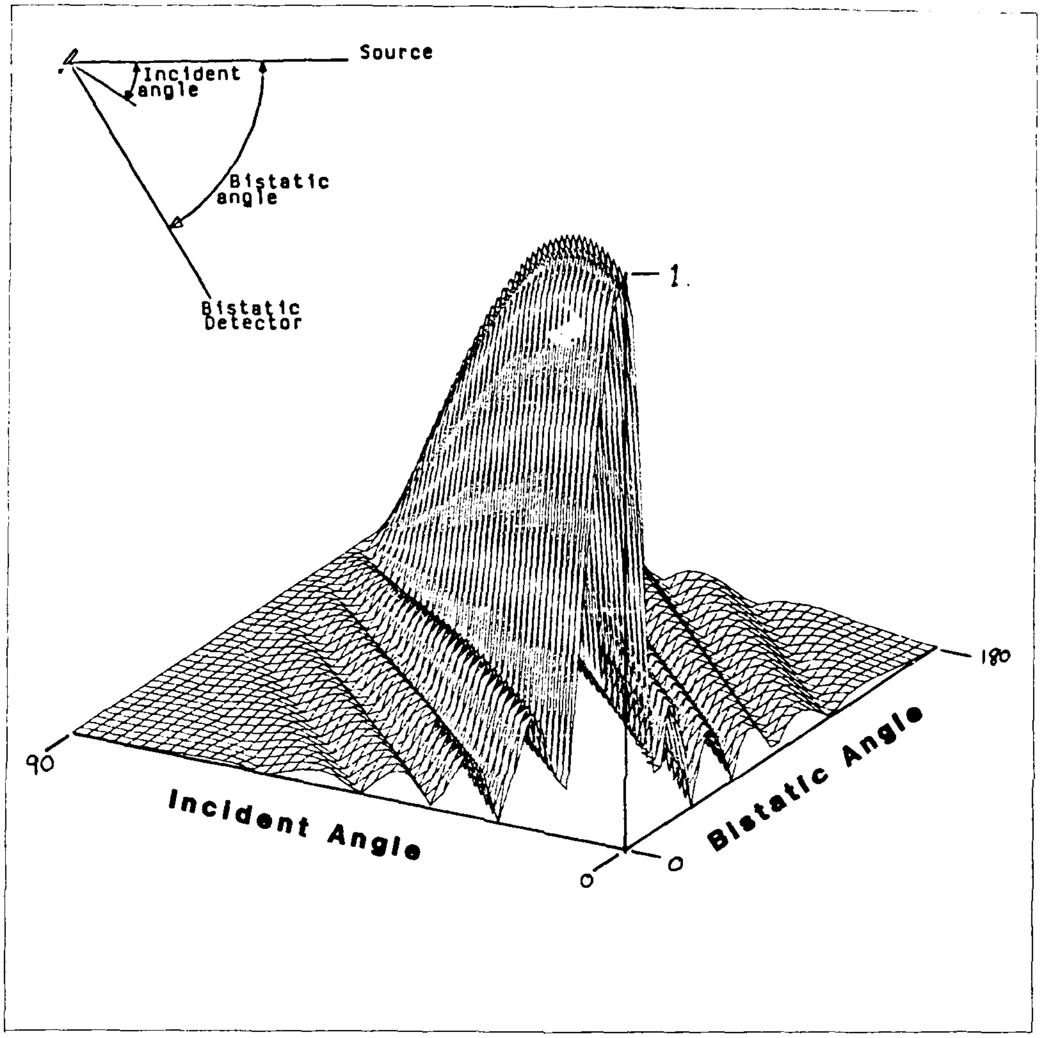

Figure 1 *Representation of two dimensional reflectivity as a function of bistatic and incident angles.*

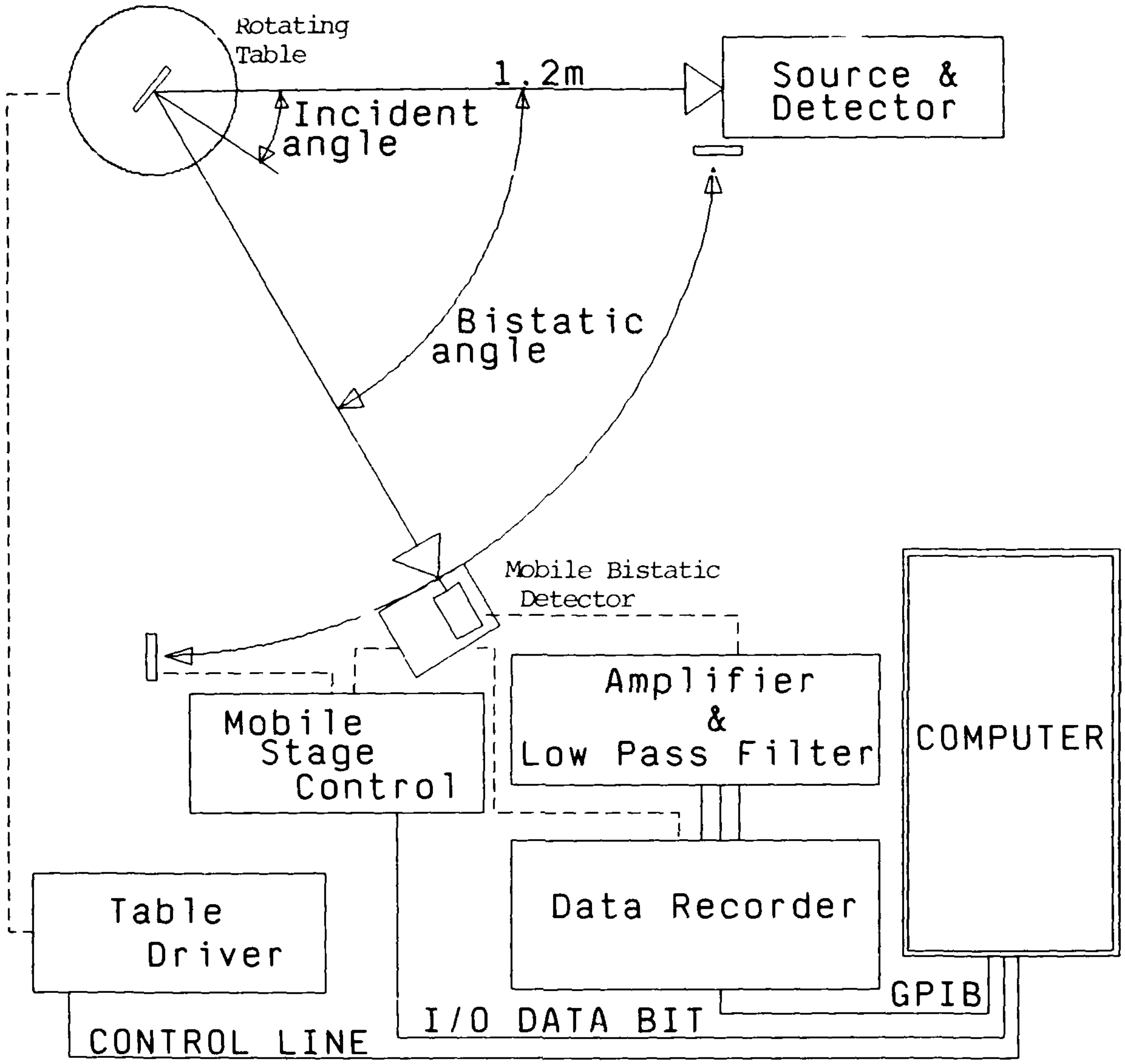

Figure 2 System Schematic

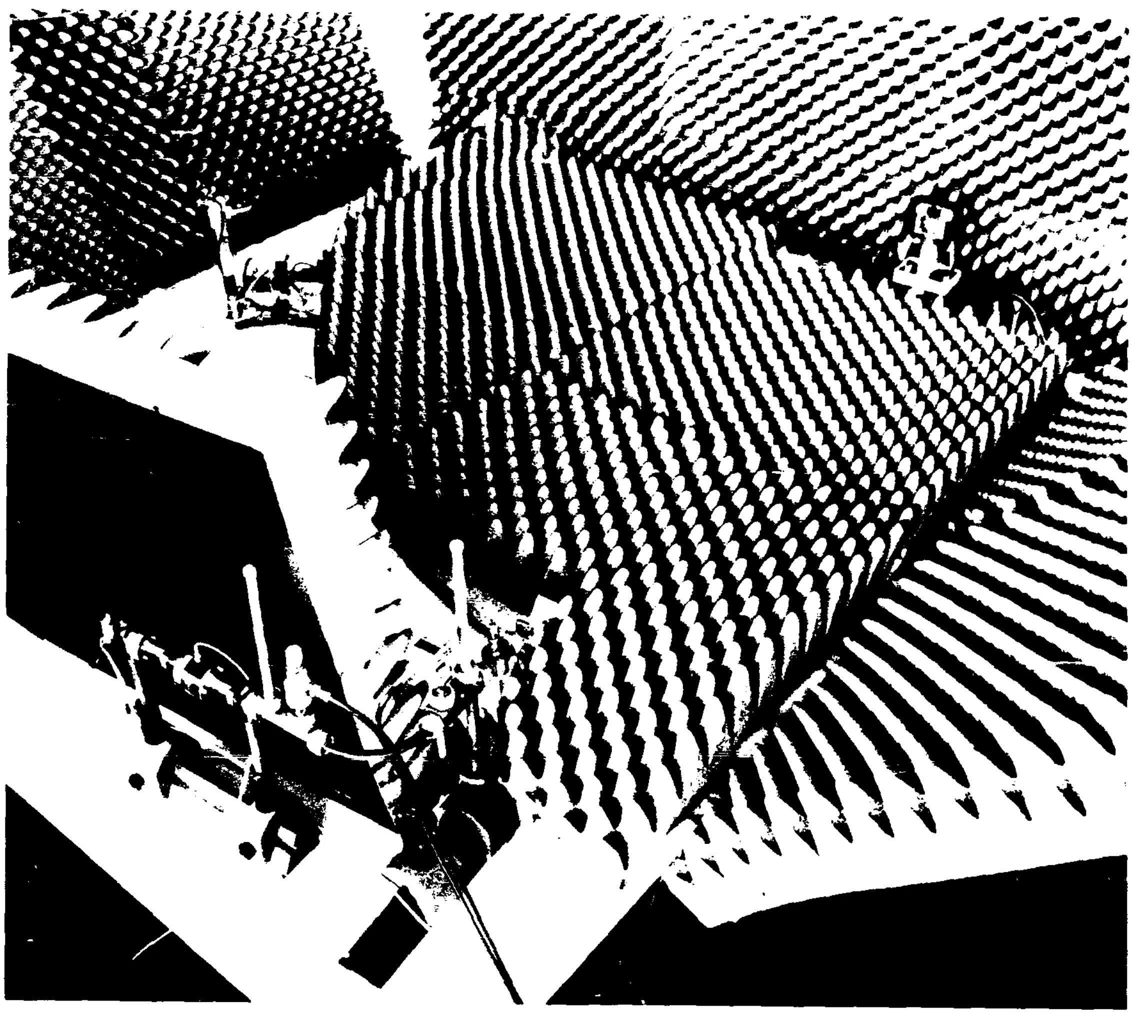

Figure 3 *Reflectivity Facility. Source and backscatter detector is shown in foreground. Bistatic detector on mobile arm - top left. Sample holder - top right. Radar absorbing material lines the top and sides of the supporting bench.*

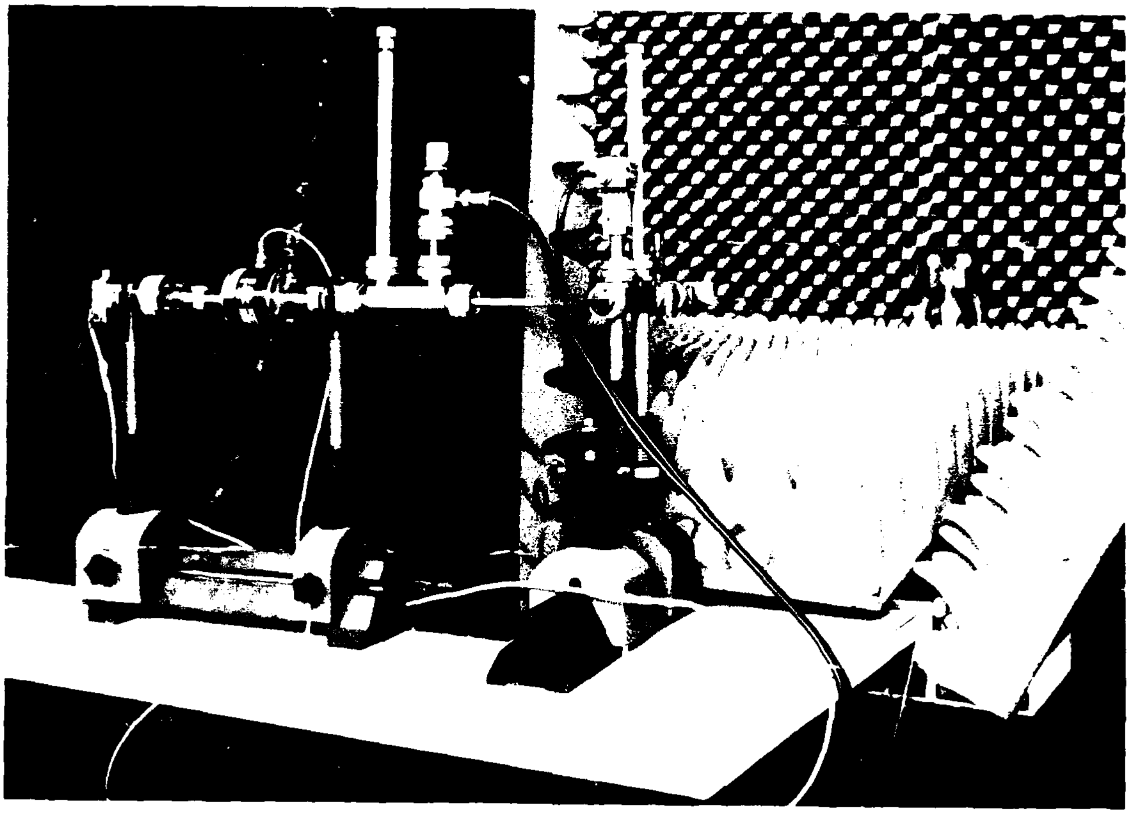

Figure 4 Source and backscatter detector with target holder in background.

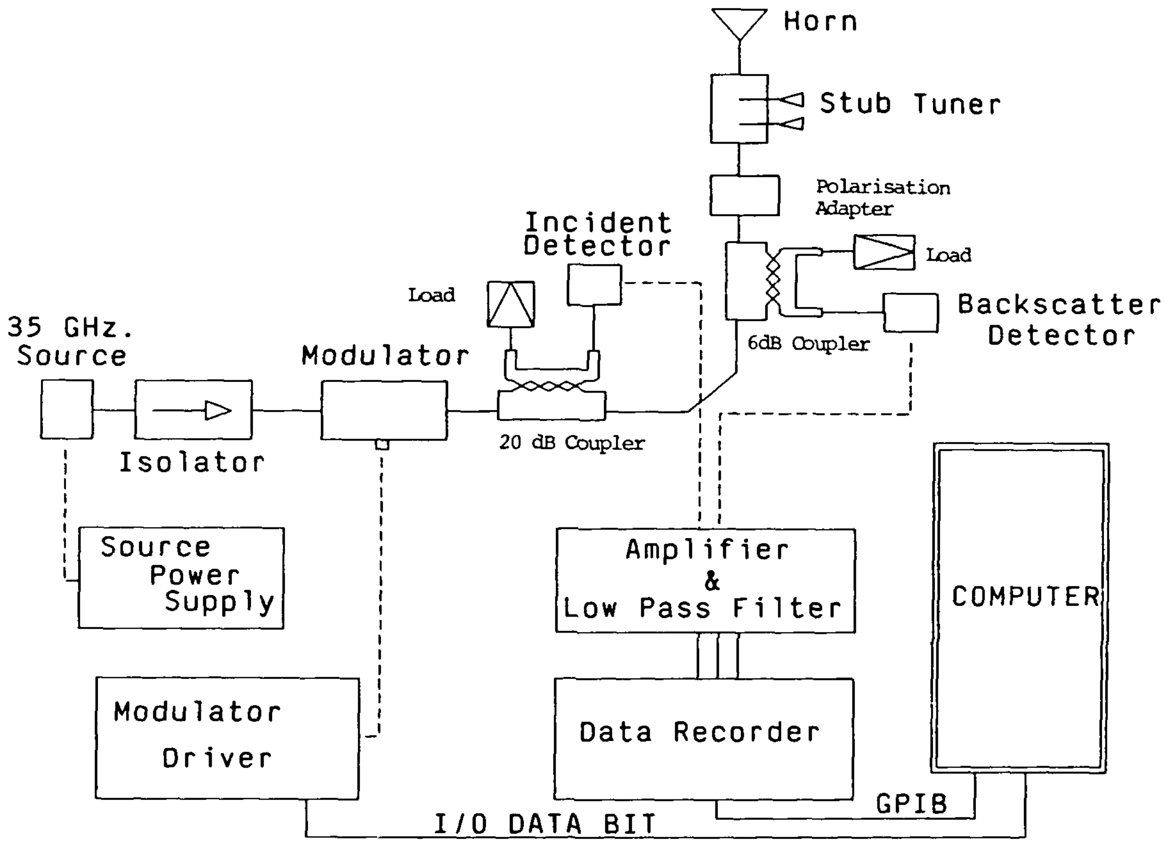

Figure 5 Schematic of source and backscatter detector and its associated instrumentation.

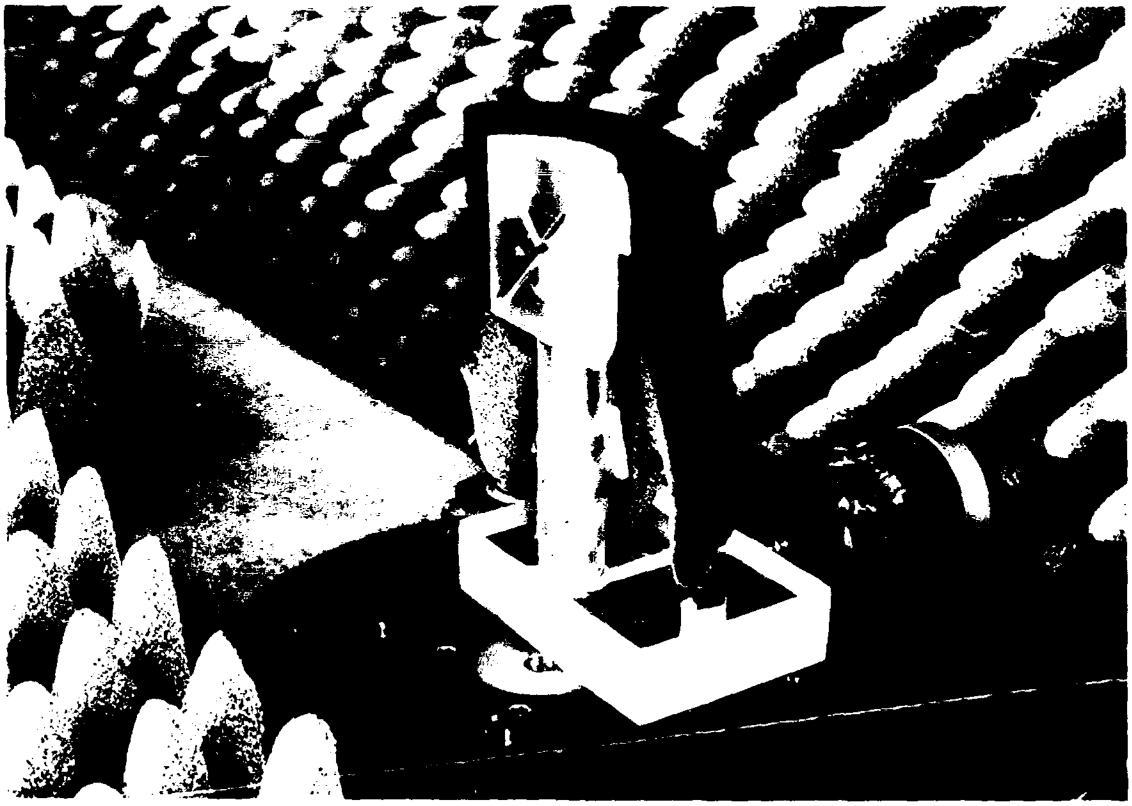

Figure 6   Flat plate sample holder on rotating table.

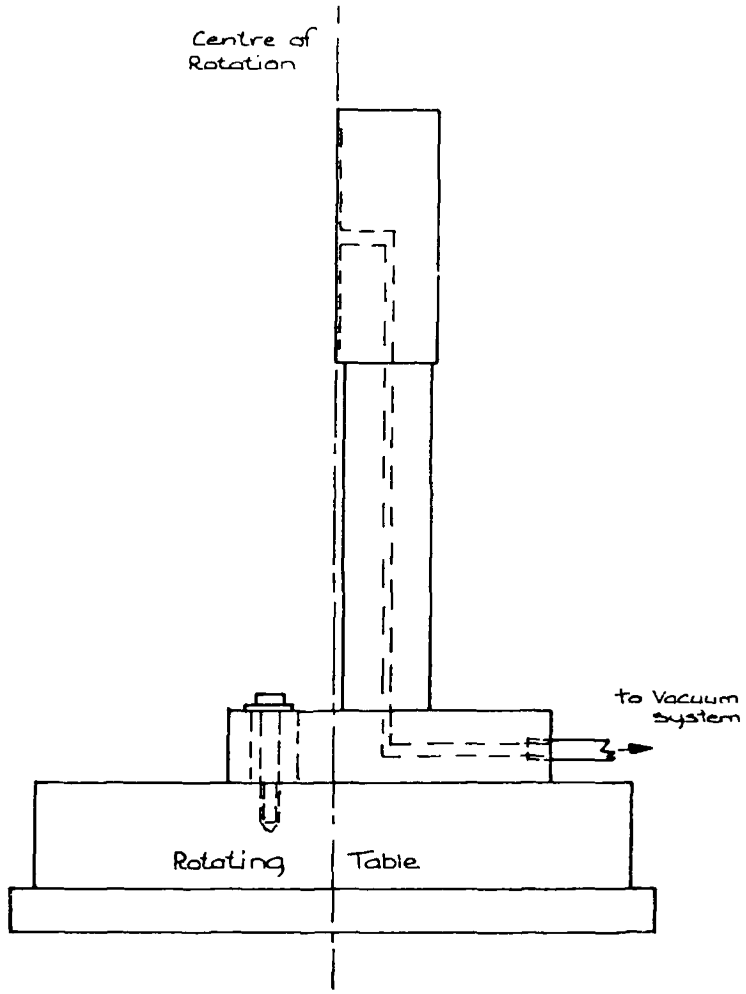

Figure 7 Sample holder, showing rotating table configuration and vacuum system.

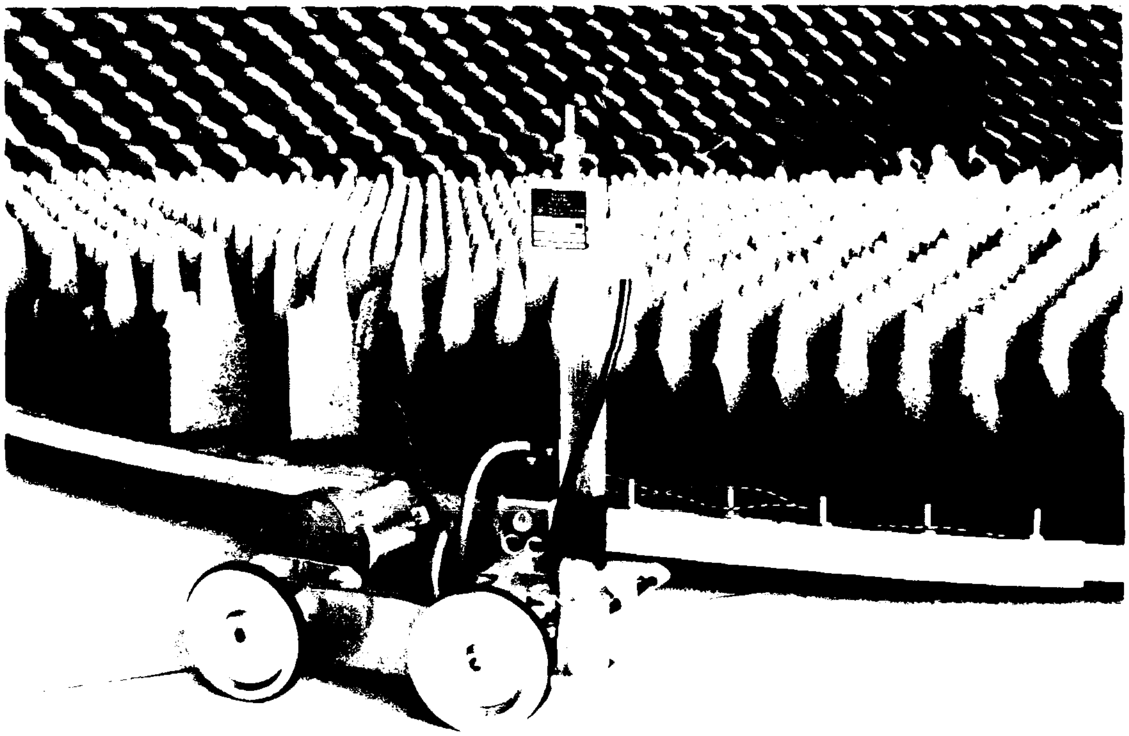

Figure 8 Bistatic detector on mobile stand with target area in background.

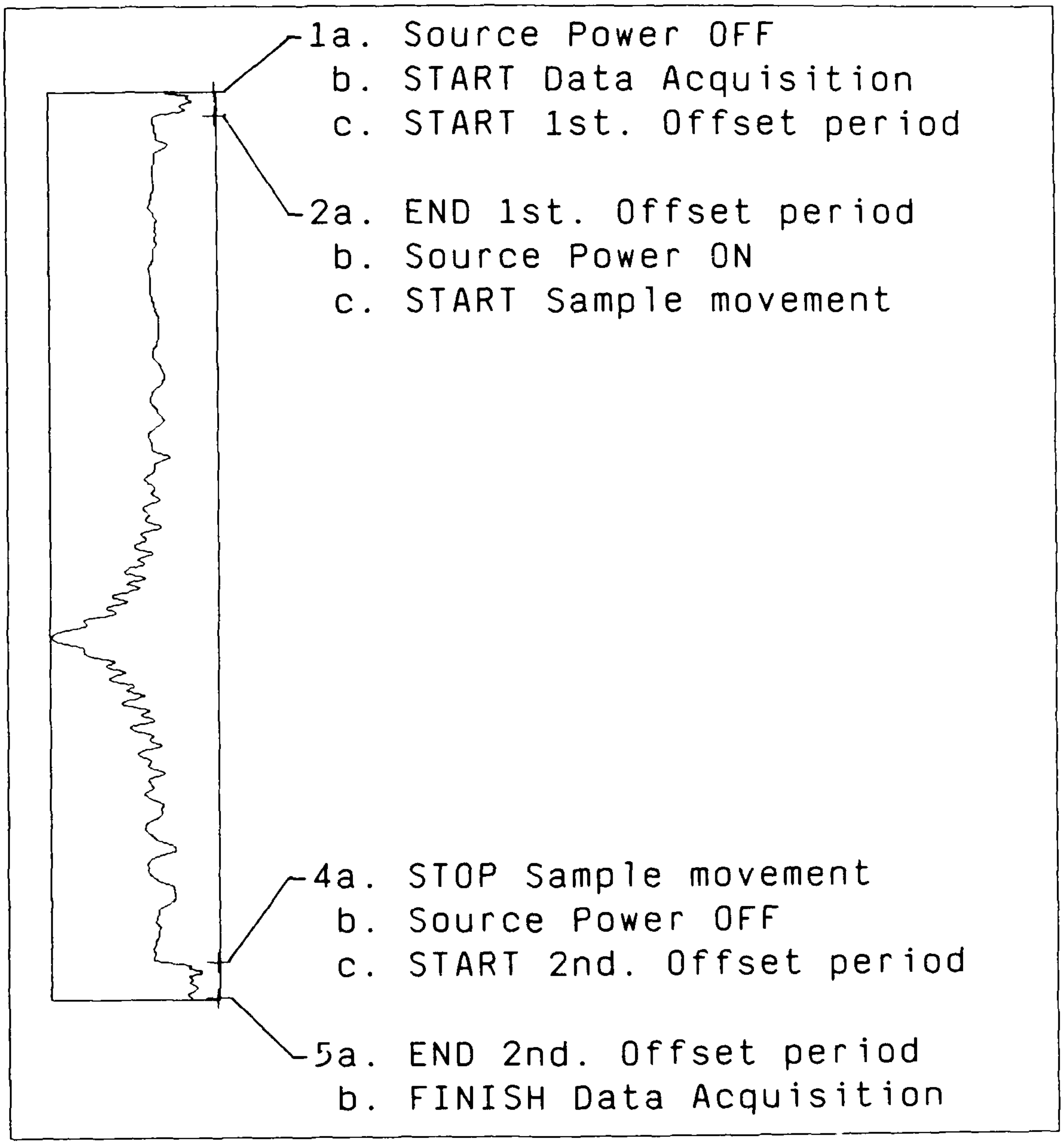

Figure 9 Order of events for acquisition of data as compared to a typical detector record.

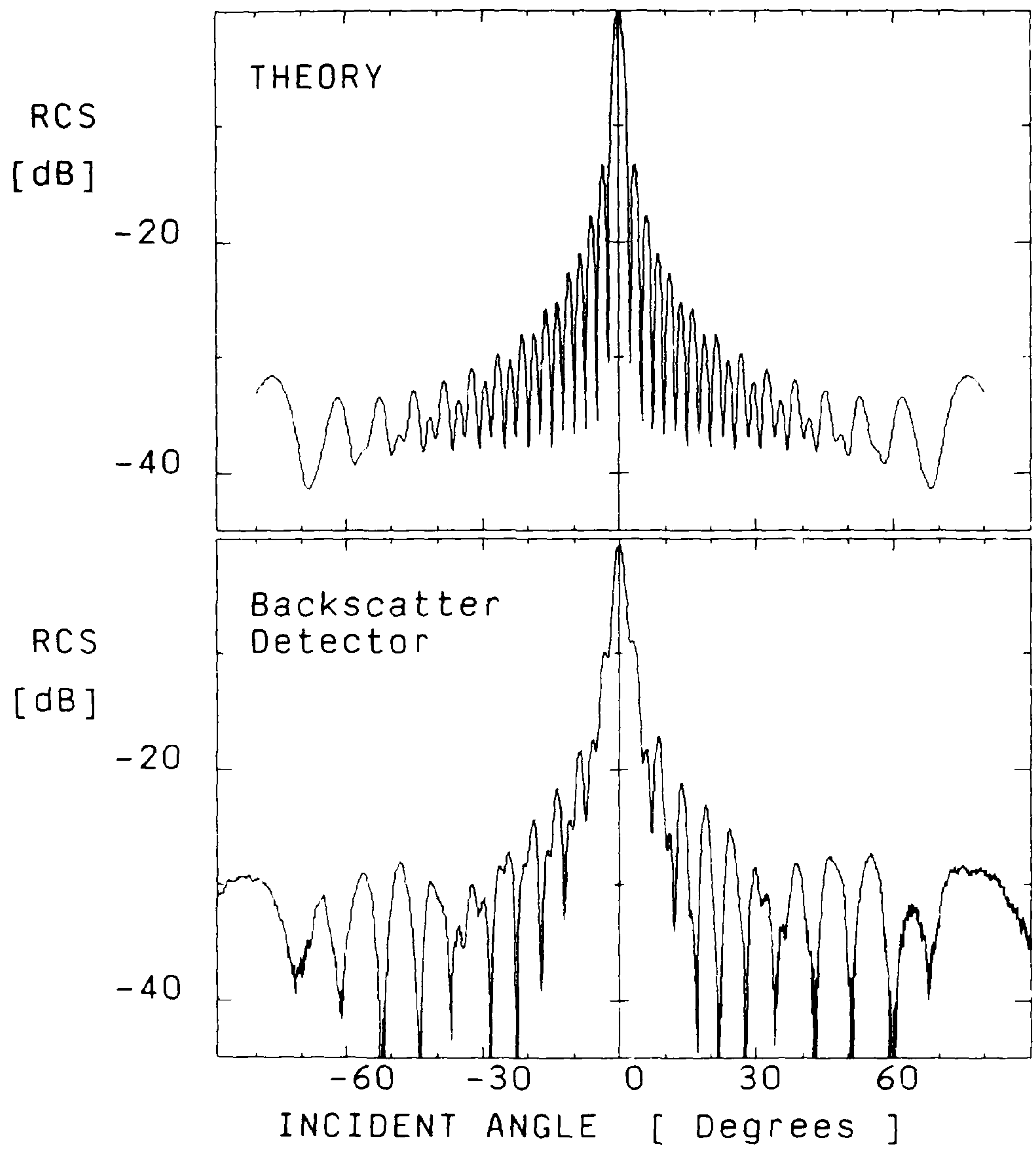

Figure 10 *Comparison between experimental signal from a metal plate and the calculated geometrical optics results from equation 1.*

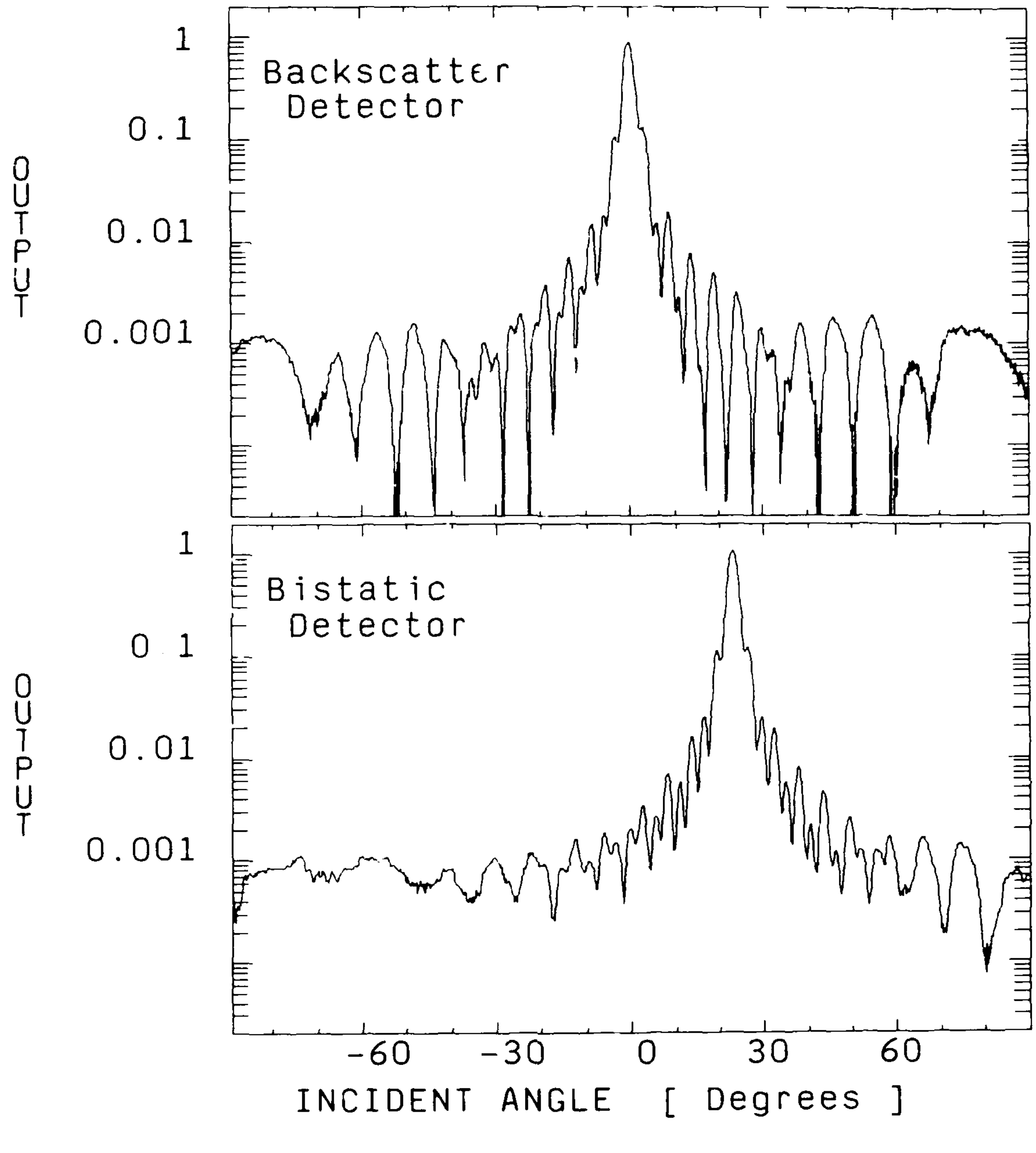

Figure 11 *Normalised signal from bistatic and backscatter detectors when sample is rotated. The bistatic angle has been set at 45 degrees.*

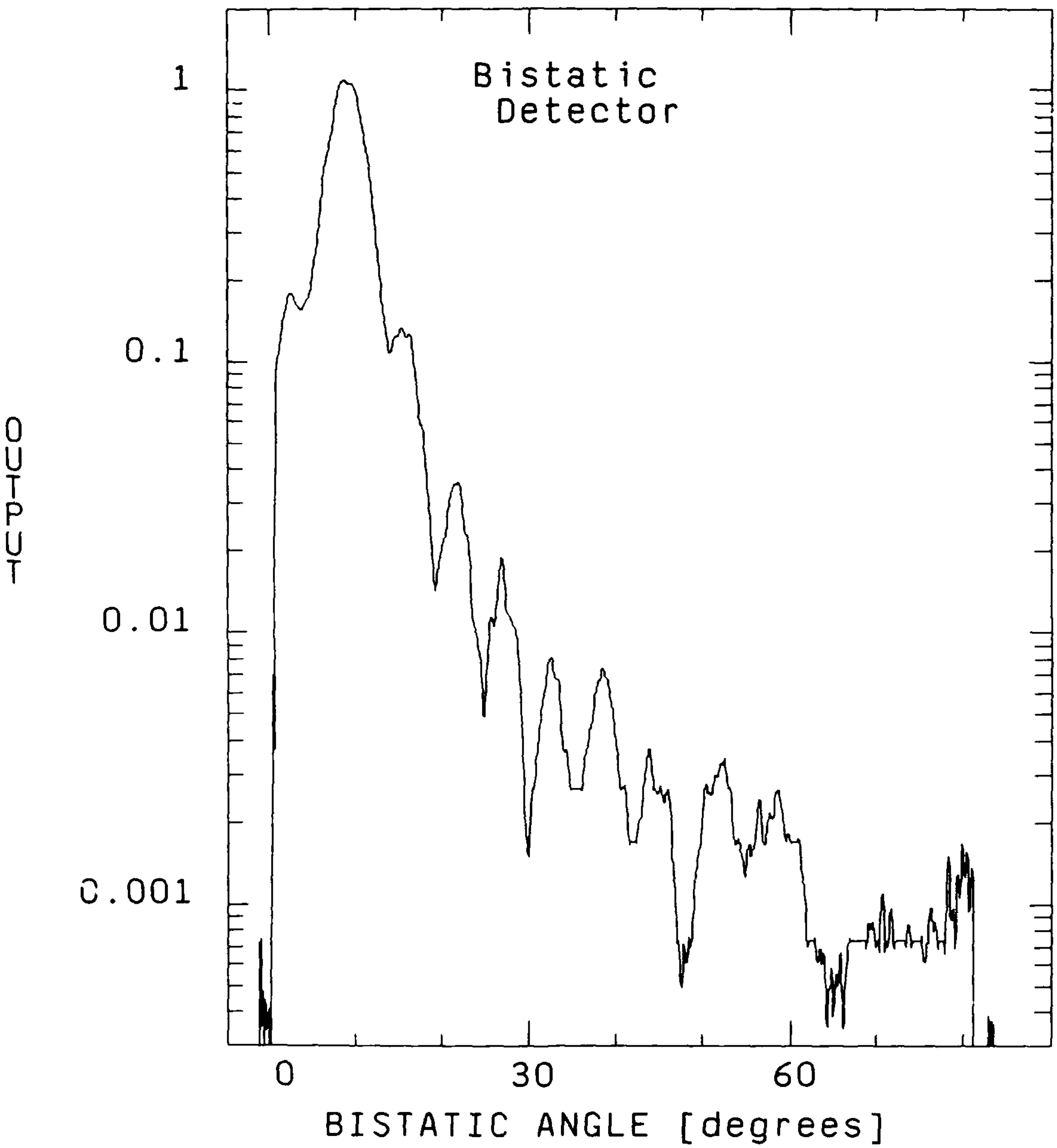

Figure 12 *Normalised bistatic detector signal obtained when the bistatic detector is rotated about the target. The incident angle has been set at 5 degrees.*

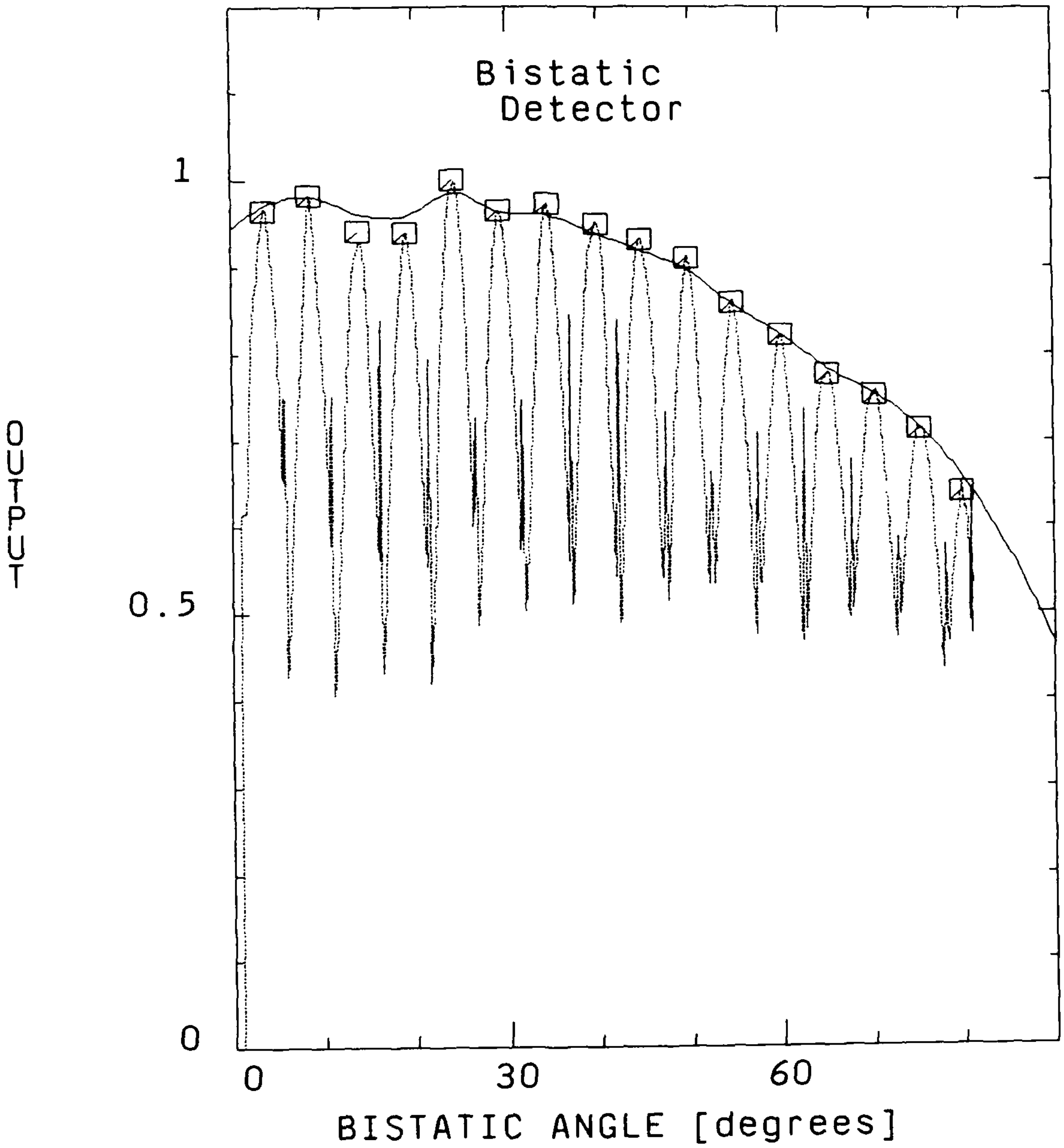

Figure 13 *Normalised signal from bistatic detector when specular reflection is being measured. The peaks marked are extracted to be used as the specular reflection data points.*

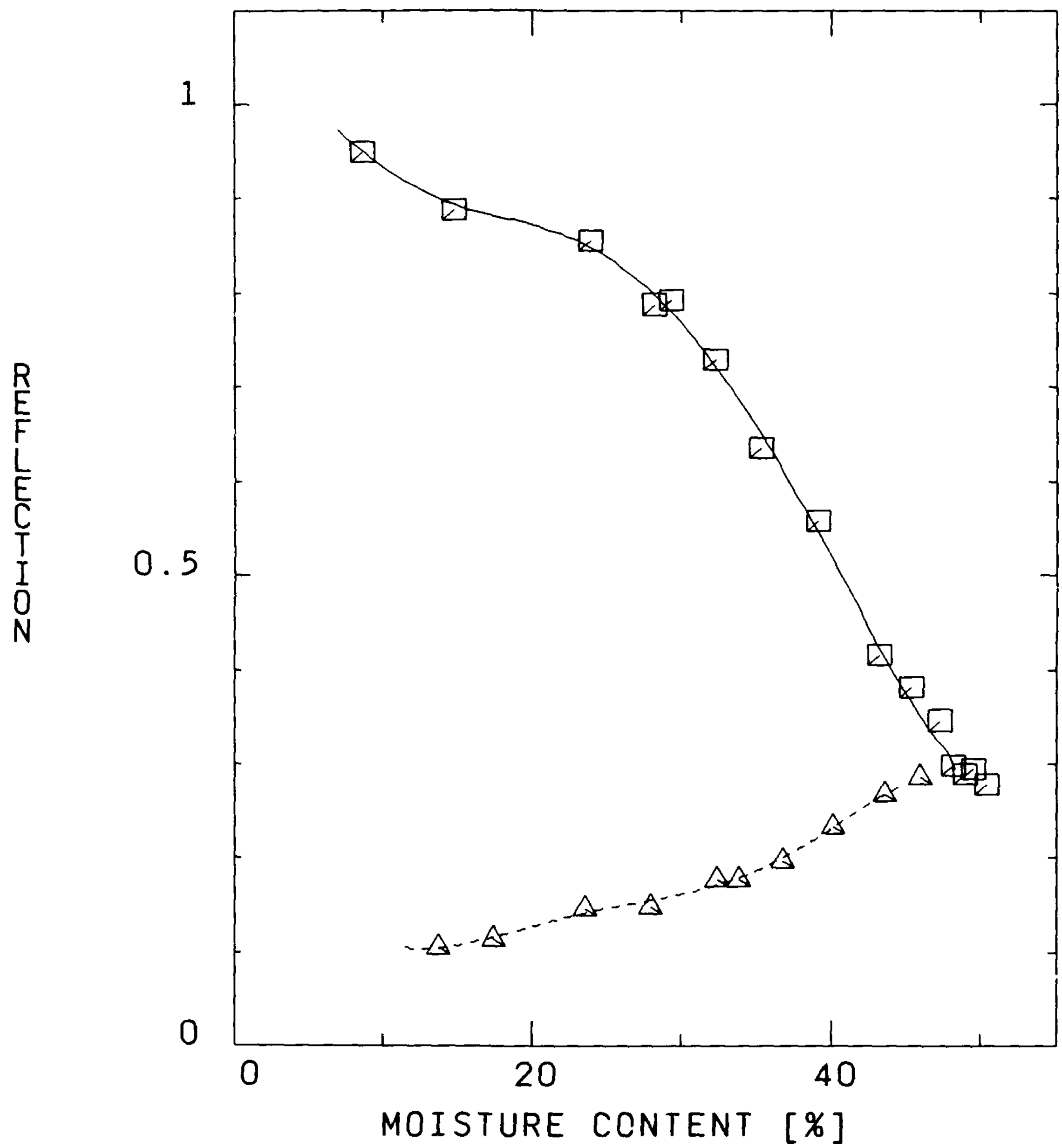

Figure 14 *Reflectivity of leaves placed on a metal plate (squares) and onto white posterboard (triangles).*

SECURITY CLASSIFICATION OF THIS PAGE **UNCLASSIFIED**

DOCUMENT CONTROL DATA SHEET

REPORT NO.	AR NO.	REPORT SECURITY CLASSIFICATION
MRL-TN-559	AR-OO5-729	Unclassified

TITLE

The measurement of surface reflectivity at millimetre wavelengths

AUTHOR(S)	CORPORATE AUTHOR
P.W. Dixon and K.J. Gaylor	DSTO Materials Research Laboratory PO Box 50 Ascot Vale Victoria 3032

REPORT DATE	TASK NO.	SPONSOR
August 1989	DST 85/193	DSTO

FILE NO.	REFERENCES	PAGES
G6/4/8-3743	6	30

CLASSIFICATION/LIMITATION REVIEW DATE	CLASSIFICATION/RELEASE AUTHORITY
	Chief, Underwater Weapon and Countermeasure Systems Division

SECONDARY DISTRIBUTION

Approved for public release

ANNOUNCEMENT

Announcement of this report is unlimited

KEYWORDS

Bistatic reflection	Reflection	Specular reflection
Electromagnetic properties		Monostatic reflection

SUBJECT GROUPS 0063H

ABSTRACT

An experimental facility has been constructed to measure the surface reflectivity of materials at millimetre wavelengths. The facility can be used to measure the bistatic, monostatic or specular reflection from flat samples at horizontal, vertical or cross polarisations. The reflectivity of some representative materials of defence interest has been measured at 35 GHz.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED